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PRINCIPAL INVESTIGATOR: Gerald A. Higgins, Ph.D.
Dwight A. Meglan, Ph.D.
Gregory L. Merrill

CONTRACTING ORGANIZATION: High Techsplanations, Incorporated
Rockville, Maryland 20852-4874

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FOREWORD

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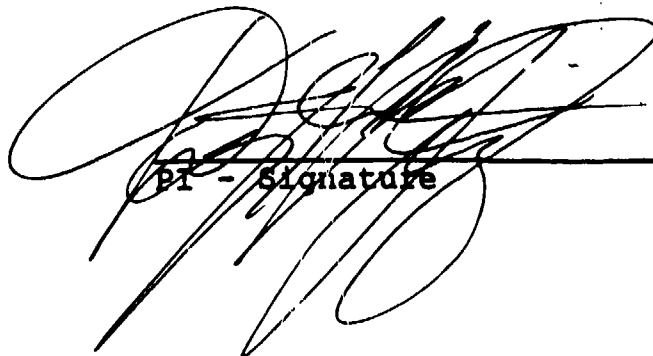
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I. Introduction

The objective of creating a computer simulated virtual environment for medical training is to provide a level of training not possible using traditional methods. In this project, we are developing the software tools and the medical content to produce a virtual reality simulation of the surgical removal and repair of abdominal organs with visual and haptic features reflective of the actual surgical procedure. These procedures are components of trauma management in the battlefield setting, where massive blunt or multiple penetrating injury requires the repair and removal of abdominal organs.

Traditional techniques for teaching trauma procedures have depended largely on the existence of a sufficiently large number of proctors with adequate surgical skills to teach trauma procedures. Other approaches include practice on animals, but animal models of injury often do not reflect human trauma, and raise a host of ethical issues concerning procuring and maintaining animals for surgical training. Also, practice on humans and animals precludes the ability to repeatedly rehearse specific components of the procedure that may prove challenging or require finely tuned motor skills. An additional concern is that Department of Defense (DoD) hospitals are usually not regional trauma centers, so that physicians and allied health personnel in the military may not obtain significant exposure to human trauma cases for training purposes.

Although the airline industry and DoD have used flight and battlefield simulators for many years, several technical challenges have limited the use of computer-based simulation technology in medical education. A flight simulator is easier to implement than a surgical simulator; the terrain of the ground is fixed and rigid, and an airplane simply moves through a path above this terrain. A surgical simulator, on the other hand, is more complex. The terrain of the body (the internal organs) must be interacted with, and they must flex, be able to be cut and then re-attached. This manipulation involves much greater computational sophistication. The organs in the body must be programmed with physiological behaviors and basic principles of physics so they respond appropriately when they are cut, tugged, and stretched. In addition, the surgical simulator must have knowledge of how each instrument interacts with the tissues. For example, a scalpel will cut tissue when a certain amount of pressure is applied; however, a blunt instrument may not.

Virtual reality technology holds tremendous promise for surgical trauma training, because it offers physicians, battlefield and emergency medical personnel the opportunity to practice in an environment where mistakes do not adversely affect patients. An optimal training simulator replicates the physical and physiological properties of the real procedure. In addition, it offers the ability to automatically track and evaluate performance, provides the option of different procedural scenarios, as well as simulating a range of surgical complications and anatomical anomalies.

Since a computer simulated virtual environment for medical training must provide a level of training not possible using traditional methods, only those virtual environments that offer sufficient realism will constitute a commercially viable alternative to established practice on cadavers, animals and patients. Realism in the context of virtual environments for medical training relates to how the anatomical structures appear, how life-like the interaction is with the anatomy, and how it behaves when one interacts with the anatomy.

Computerized surgical simulations will make a tremendous impact in improving surgical morbidity and mortality. Studies have shown that, for a wide range of diagnostic and therapeutic procedures, doctors doing their first few to several dozen cases are much more likely to make a greater number of errors. Adequate proctoring of learners by experienced surgeons is cumbersome, as there are few surgeons experienced enough in the techniques to proctor their colleagues. It is exceedingly difficult for physicians, particularly those in rural areas, to travel to larger medical centers for training. The requirement also places a burden on experts who could become overwhelmed with proctoring requests.

Because the anatomical models used in the surgical simulator can be based on clinical studies (CT and MR scans), future versions of the proposed simulation could be individualized on a patient basis -- to allow pre-surgical planning and allow physicians to practice difficult operations. Surgical trauma simulators will allow physicians to communicate surgical scenarios with their peers and exchange ideas regarding surgical management of patients. Furthermore, these simulations could be transported to rural areas to allow the dissemination of surgical techniques. Significant operative risk reduction will be made possible by the development of a simulator which would allow transference of skills from the simulation to the actual patient contact.

II. Body

Realism in the context of virtual environments for medical training relates to how the anatomical structures appear, how life-like the interaction is with the anatomy, and how it behaves when one interacts with the anatomy. To accomplish this goal, the project is bringing together technologies from diverse areas including movie special effects, computer graphics, motion tracking, medical content development and human factors engineering.

Technical progress during year two of this effort has been made in the following areas:

- a. Development of haptic feedback interface device
- b. Refinement in computer modeling technology
- c. Acquisition and processing of polygonal/segmented abdominal anatomy database
- d. Development of efficient patient specific visualization algorithms
- e. Development of fluid flow simulation model
- f. First implementation of a medical simulation software architecture
- g. Development of educational content

The following section provides additional detail on each of these achievements and the accompanying video provides a demonstration.

a. Development of haptic feedback interface device

Visual realism and haptic fidelity are both critical elements to a realistic trauma simulation. Current technology in tactile feedback robotics does possess the fidelity necessary to allow realistic manual palpation of tissues and blunt dissection that is necessary for creating out an instrument-based abdominal trauma simulation system. Our research efforts have focused on a technical solution integrating robotics, position tracking, and physics-based simulation techniques.

Initial evaluations were carried out to assess the applicability of classic blue screen technologies to allow simulation of full hand manipulation of organ models. These techniques are more fully described in the previous progress report. Experiments were carried out to test the computer techniques needed and a survey of available and near future sensor systems was performed. It was concluded that while the benefits of physical model based simulation are significant, the technological innovations required are quite significant. Therefore, the more classic approach of manipulating simulation models via haptic interface devices for virtual surgical instruments would be more appropriate and developments along this line are continuing.

We have integrated two versions of the SensAble Technologies PHANToM device into our TELEOS simulation environment and given a number of public demonstrations of this technique's potential. The three motors of the PHANToM are able to replicate high fidelity haptic "images." The PHANToM is limited in its DOF for active feedback and based on these limitations, we have focused our efforts in the second and third quarters of year two on a six-DOF device - The Cybernet, Inc. robot. Our initial demonstrations

developing a vascular access simulator have shown that graphic overlay techniques can be used with physical models and integrated with a six degree-of-freedom (DOF) force feedback robot with a custom stylus designed as a proxy needle and catheter. The enclosed video illustrates current progress with this system.

b. Refinement in computer modeling technology

Refinement in computer modeling has included faster, more general collision detection software which can be used with large polygonal models and the development of a number of medical simulation techniques based upon the Performer real-time simulation libraries from Silicon Graphics. We have begun to explore new techniques in fast-finite-element modeling which will be applied to the local deformation of the abdominal organs.

Dr. Morten Bro-Nielsen has recently joined our staff and much of his research has focused on these techniques (Bro-Nielsen (1995,1996,1997), Bro-Nielsen and Cotin (1995,1996), Cotin et al. (1996)). We are beginning to look at their application to the trauma simulation.

c. Acquisition and processing of polygonal/segmented abdominal anatomy database

We have acquired a comprehensive segmented abdominal dataset of the Visible Human male through a subcontract with Visible Productions, LLC, Ft. Collins, Colorado. We have completed initial processing of this data for real-time interaction. This processing included decimation of the models to minimize the polygon count and rendering as solid surface models. On the Silicon Graphics Infinite Reality system we have achieved frame rates of approximately three frames per second on this complete dataset without culling or other processing techniques that are yet to be implemented. The anatomic structures currently modeled and decimated include the following:

Abdomen

diaphragm, liver and gall bladder (including hepatic artery, hepatic vein, portal vein and biliary system), spleen, stomach, duodenum, entire colon and rectum, and greater omentum.

Kidneys

Both kidneys including the ureters, renal artery, and renal vein up to interlobular branches, renal pelvis, major and minor calices.

Spine

Rib Cage

Pelvis

Skin

d. Development of efficient patient specific visualization algorithms

The availability of hardware with advanced 3D graphics features opens the door to new kind of applications and provides new power to algorithms that were not before applicable in interactive applications. One of the most interesting features now available on the new generation Silicon Graphics workstations is the ability to define volumetric textures. A volumetric texture is a 3D region where texture values are stored in a three dimensional grid. Each polygon inside the volumetric texture assumes the texture values it intersects. This graphics feature provides a new way to apply interactive algorithms for Volume Rendering resulting in fast rendering updates. Our technology allows direct anatomical visualization of patient specific and Visible Human volume data.

These volume visualization algorithms allow display and analysis, interactively of volumetric data from CT or MRI scanners and full color data set (the Visible Human data). The software runs on workstations from Silicon Graphics (High and Maximum IMPACT) and on Onyx Reality Engine and the new Infinity Reality. Features include infinite and interactive point of view, with arbitrary section planes.

It is anticipated that the technology will integrate with haptic input devices, allowing the user to feel the data as a real object. This will open the door on surgical simulation directly on patient data without any kind of computational expensive transformations. Research is continuing on the development of interactive volume deformation and cutting.

The current implementation includes the following:

- Full support of gray-scales (MR/CT) and color data.
- Resolution up to 256x256x384 voxel in interactive frame rate
- Interactive manipulation of point of view
- Interactive advanced look-up table manipulation to select different kinds of tissues
- Arbitrary clipping plane to inspect internal structures
- Interactive scaling of models and brick explosions
- Depth resolution ranging from 1 to 1,000 polygon planes

This technology is being incorporated into a tool set for the medical visualization industry in a product we are calling the TELEOS Voxel Visualizer™ (T-Vox™). Much of the algorithmic research for this code has been accomplished through this DARPA grant. The refinement of this software as a product, is supported by HT's cooperative research agreement with the US Department of Commerce's Advanced Technology Program.

e. Development of fluid flow simulation model

Realistic fluid flow has been a significant challenge for real-time simulation. Due to differences in the physicals manifestations of flow, two different algorithmic techniques are needed to simulate intravascular flow and flow through a hemorrhage or cut. We have developed a simulation approach, which has now been incorporated into our interventional radiology simulation system, that is based on a three dimensional, computational grid composed of nodes of fluid automata. This technique allows for realistic models of fluid

flow including diffusion and pressure wave propagation to be incorporated into the simulation system and for changes in intravascular flow to result from systemic changes.

f. Initial implementation of a medical simulation software architecture

Computational demands for surgical simulations have been the biggest bottle neck for interactive processing rates. Among the most significant accomplishments during year two of this project has been our progress in the development of a flexible and expandable distributed processor software architecture specifically designed to meet the needs of medical simulation. A preliminary version of the Real-time Control System (RCS) has been implemented. Our implementation runs as a single simulation system distributed amongst a number of machines which can be of different architectures and so we are calling it the Distributed Real-time Control System (dRCS). The resulting benefits to speed have been demonstrated with a number of examples allowing simulations to control movements of graphics running under the Performer real-time simulation libraries. We have achieved an increase of over 200% in performance by having the visualization and computation parts of the simulation running on different computers. dRCS is currently running on both SGI hardware and Windows '95/Intel Pentium-based personal computers. We are now implementing dRCS in our prototype interventional radiology simulator. The core research for this software has been the result of this DARPA grant. The development of this technology into a reusable library of code has been supported by our ATP development agreement.

g. Development of educational content

In discussions with Drs. Christopher Kaufmann and Howard Champion, the following abdominal trauma surgery procedures were recommended and prioritized, with an emphasis on technical feasibility in the simulation environment:

- splenectomy
- removal of a 'shattered kidney'
- liver 'packing'
- laparotomy, with an emphasis on examination of the small intestine

'SPLENECTOMY' PROCEDURE

The following protocol is a general description of this procedure should be implemented, with the caveat that additional input both from the Medical Advisory and Core Technology Group will undoubtedly lead to subsequent revisions. Text and graphics are adapted from: E.E. Moore (1989) 'Splenic Injury', in: (Eds. H.R. Champion, J.V. Robbs, D.D. Trunkey) Rob & Smiths Trauma Surgery, Butterworths, London, pp 366-373.

(1) Abdominal exploration

The user will face a draped mannequin with the abdomen exposed. The user will select a scalpel and make a vertical incision on the midline, extending from the xiphoid process to just below the umbilicus. The user will be prompted by the program that a splenectomy needs to be performed. In normal practice, the full extent of intra-abdominal injuries would be assessed by a full laparotomy.

(2) Mobilization of the spleen

The spleen has the feel of a dense sponge encapsulated in a fibroelastic coat and tethered deep in the left upper abdomen by thin connective tissue ligaments. The lienophrenic and lienorenal ligaments are generally thin and avascular. The lienocolic ligament usually contains large blood vessels (i.e., it bleeds when severed or torn), and the lienogastric ligament contains the vasa brevia and left gastroepiploic blood vessels. The lienogastric ligament is triangular in shape, with the apex directed cephalad. The superior pole of the spleen sits dangerously close to the greater curvature of the stomach, and the tail of the pancreas also sits close to the posterior hilum of the spleen, an organ which cannot be even slightly damaged without serious consequences.

(3) Retraction of the spleen

The user threads a nasogastric tube into the stomach to decompress the stomach. The user retracts the spleen anteromedially while maintaining traction on the left abdominal wall. The taut lienorenal ligament is cut well away from the lateral margin of the spleen. Sharp dissection is continued across the lienophrenic ligament to the esophagus.

(4) Rotation of the spleen

Following complete division of the lienorenal and lienophrenic ligaments a plane is developed posterior to the pancreas with blunt dissection. Once mobile, the spleen is gradually rotated into the abdominal wound. Resistance inferiorly requires division of the lienocolic ligament.

(5) Removal of the spleen

The anterior splenic hilum is exposed. The lienocolic and lienogastric ligaments are incised, with special care taken to isolate and ligate large vessels such as the splenic artery. Next the posterior splenic hilum is exposed and cut, necessitating careful dissection to avoid damaging the tail of the pancreas. The spleen is removed from the abdomen.

'SHATTERED KIDNEY' PROCEDURE

A "Shattered Kidney" formally refers to multiple lacerations of the kidney with contained or disrupted fragments, often held together by the remains of the renal capsule (McAninch

and Carroll, 1989). This usually results from severe blunt or penetrating trauma to the kidney. McAninch and Carroll (1989) provide the standard method for classifying the extent of renal trauma. Among civilians, 80% of all renal trauma is due to blunt trauma, with motor vehicle accidents accounting for the vast majority of cases (Chambers, Champion and Edson (1989). Although the kidneys are well protected by the ribs, vertebrae, back muscles and abdominal viscera, they are the most commonly injured organs in abdominal trauma. In the battlefield setting, the "Shattered Kidney" can be caused by extensive penetrating wounds, such as caused by bullets or shrapnel, or by massive blunt trauma. In both the emergency room and in the battlefield, the best approach for the "Shattered Kidney" is rapid complete or partial nephrectomy (Guerriero, W.G. and M. Coburn (1994).

The following procedure has been adapted from Taylor, D.L. and W.R. Fair (1985):

Major indicator of serious complications: Loss of continuity of the renal capsule and distraction of fragments.

If visualized or suspected, major peritoneal hematoma indicates the necessity for opening of the retroperitoneum and exploration of the kidney. In the emergency setting, injudicious exploration may lead to unnecessary nephrectomy, however, several studies have shown the first 2-3 days offer the best window of opportunity for corrective surgery.

Surgical approach:

(1) Abdominal exploration

Make a vertical midline incision in the abdomen.

Begin exploration of the abdomen, following establishment of hemostasis - include debridement of the path of any penetrating object(s) or missile(s). The retroperitoneum is approached along the aorta at the root of the mesentery.

If you find the existence of a large retroperitoneal hematoma or other indications of a major renal trauma, open the retroperitoneum medial to the inferior mesenteric vein and identify the aorta.

Indications for surgical exploration of major trauma (McAninch and Carroll (1989)):

- Expanding or uncontained hematoma
- Pulsatile retroperitoneal hematoma
- Major urinary extravasation
- Non-viable renal parenchyma (loss of more than 15% of the kidney)
- Vascular injury

Please note that some of these indications can only be determined using pre-operative imaging methods, which may not be practical in a battlefield setting.

(2) Exploration of the retroperitoneal space

Dissect the peritoneum cephalad along the anterior surface of the aorta to expose the left renal vein crossing the aorta.

Vascular control is obtained by clamping the renal vein and artery at their origins from the vena cava and the aorta. (mistake possible here - if the surgeon strays too far cephalad and lateral to the aorta, the splenic artery and vein may be mistaken for the left renal artery and vein).

Reflect the colon prior to exploration of the retroperitoneal space.

Use the principles of exploration outlined by Scott and Carlton and their colleagues (Scott, Carlton, and Goldman (1969); Scott and Selzman (1966):

- Obtain early vascular control
- Debride any devitalized tissue
- Obtain hemostasis by suture ligation
- Insure watertight closure of the collecting system
- Approximate the parenchymal margins
- Obtain extraperitoneal drainage of the renal fossa

(3) Analysis/corrective surgery of the kidney

Substantive damage limited to a portion of the kidney usually indicates partial nephrectomy.

Disruption of the collecting system usually occurs through damage to the calyceal fornices. This repair involves watertight suturing of the collecting system at the level of the fornix.

If bilateral renal damage is present, the kidney with the best possibility of recovery is repaired first.

Transcapsular damage is often present in major renal injuries, especially those with penetrating injuries (e.g., bullets, shrapnel; see Scott, Carlton and Goldman (1969)). In these cases:

- Ligate all major vessels.
- Use a watertight closure for the collecting system.
- Close the capsule with running or interrupted sutures.
- Use diverting pyelostomy for clots in the renal pelvis.
- Make sure that all devitalized tissue is debrided.

III. Conclusions

The following conclusions can be drawn from the second year of the project:

- 1) We have continued to make progress in developing techniques to allow the direct manipulation of virtual tissues, as necessary for trauma simulation. We created several new approaches to including haptic feedback for trauma surgery through the integration of robotics and physics-based tissue modeling into a real-time simulation architecture.
- 2) We have continued to advance the computer modeling technology necessary for medical simulation. We have demonstrated interactive models representing both flexible and rigid structures. We are continuing to develop techniques for volume deformation and surface warping and have begun work incorporating fast finite element modeling into our simulation approach.
- 3) The Visible Human male dataset has been segmented to the extent necessary for the abdominal simulation. Additional processing of this data is being accomplished to add physics and physiology to the tissues and maintain interactive frame rates.
- 4) We have demonstrated the ability to render patient specific as well as color volume data at interactive frame rates.
- 5) We have implemented a novel method for real-time intravascular fluid flow taking advantage of techniques in cellular automata.
- 6) We have evaluated software architectures and have developed an expandable distributed real-time control system that allows for the assignment of multiple processors to various computational tasks of the simulation system. We have achieved significant performance increases on our benchmark simulation tests over our previous software architecture.
- 7) Numerous technology transfer activities have been accomplished, including major presentations at the 1995 Radiological Society of North America's annual meeting, The Medicine Meets Virtual Reality 4 conference, American Board of Medical Specialties, and several surgical meetings including presentation of and publications for the American College of Surgery. Eight peer reviewed publications have been published or are currently in-press.
- 8) A video demonstrating the past years simulation software development activities is included with this report.

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Merril, J., Merrill, G., Raju, R., Millman, A., Meglan, D., Preminger, G., Roy, R., Babayan, R., "Photo-realistic interactive three dimensional graphics in surgical simulation." Medicine Meets VR conference, p. 1-9, 1995.

Preminger, G., Babayan, R., Merrill, G., Raju, R., Millman, A., Roy, R., Merrill, J., "Virtual Reality Surgical Simulation." American Urological Association Inc. 1995 Annual Meeting- Las Vegas, NV.

Preminger, G., Babayan, R., Merrill, G., Raju, R., Millman, A., Roy, R., Merrill, J., "Virtual Reality Surgical Simulation." Gateway to Exploration: 12th World Congress and 10th basic Endourology Research Symposium 1994.

P R E S E N T A T I O N S

"Using Virtual Reality and Simulation Technology to Revolutionize Procedural Medical Education" Maryland Bioscience Forum, College Park, Maryland. September 16, 1996

"Virtual Reality Applications for Infusion Therapy" plenary presentation for the World Wide Clinical Symposium III, Deer Valley Utah. September 9, 1996.

"Employing Virtual Reality to Simulate Medical Procedures: Using Everything from Nintendo Games to Super Computers" plenary presentation of the Conference of Interactive Technology in Health Education, Plattsburgh, NY. June 13, 1996.

"The Biotechnology and Information Technology Industries Working Together" presentation to the joint meeting of the Bioscience Network and Information Technology Network of the Suburban Maryland Technology Council, Rockville, MD. April 11, 1996.

"State-of-the-Art in Laparoscopic Simulation" presentation to the Executive Committee of the Society of American Gastro Endoscopic Surgeons, Norwalk, CT. July 30, 1995

"Virtual Reality and Medicine" Keynote address, InfoHealth '95. Sao Paulo, Brazil. July 4, 1995.

"Interactive Multimedia: New Applications and Trends -- Virtual Reality and Medicine" invited lecture for Johns Hopkins University School of Continuing Studies. November 3, 1994.

"Virtual Reality Applications in Medical Training and Pre-Operative Planning" International Symposium on Medical Imaging, George Washington University Medical Center. June 17, 1994.

"Computer Simulations of Biological Systems" presented at the International Conference of Computer-Assisted Imaging of Embryonic and Fetal Development, sponsored by the National Institute of Child Health and Human Development, National Institutes of Health. June 23, 1994.

"Virtual Reality Applications in Medical Visualization" Invited lecture to the Australian medical visualization research community. Silicon Graphics, Inc., Sydney, Australia. September 15, 1994.

"Virtual reality laparoscopic surgical simulation -- pelvic lymph node dissection" Presentation at the International Urological Society Conference. Sydney, Australia, September 16, 1994.

"Medical Education Applications of Virtual Reality" 66th National Meeting of the American Health Information Management Association (AHIMA), Las Vegas, Nevada, October 23, 1994.

"Virtual Reality" Session Leader, FOSE Conference, Washington, DC March 23, 1994.

VI. Appendix

HT Medical MEDICAL ADVISORY BOARD

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Bethesda, MD

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